CIRCUMSTELLAR SiC GRAINS OF TYPE Z: EVIDENCE FOR EXTENSIVE He SHELL DREDGE-UP IN LOW-METALLICITY LOW-MASS AGB STARS. P. Hoppe[1], P. Annen[1], R. Strebel[1], P. Eberhardt[1], S. Amari[2,3], and R. S. Lewis[3], [1]Physikalisches Institut, Universität Bern, Sidlerstr. 5, CH-3012 Bern, Switzerland, [2]McDonnell Center for the Space Sciences and Physics Department, Washington University, St. Louis, MO 63130-4899, USA, [3]Enrico Fermi Institute, University of Chicago, Chicago, IL 60637-1433, USA.

Z grains are a rare class of circumstellar SiC grains. They have a characteristic Si-isotopic composition, falling to the ^{30}Si-rich side of the mainstream Si correlation line [1, 2]. Based on the C- and Si-isotopic compositions AGB stars, novae, and supernovae had been proposed as possible stellar sources of the Z grains. In order to set stronger constraints on their stellar origin we were searching for additional members of the Z grain family by screening ≈ 1200 SiC grains from the Murchison separate KJE (average grain size 1.14µm [3]) by high mass resolution ion imaging with the University of Bern ion microprobe (modified Cameca IMS3f).

Both ^{29}Si/^{28}Si and ^{30}Si/^{28}Si ratios have been measured by high mass resolution ion imaging. Digitized ion images of ≈ 60µm in diameter of $^{12}C^-$, $^{28}Si^-$, $^{29}Si^-$, and $^{30}Si^-$ produced by bombardment of the KJE sample with 14.5 keV Cs^+ ions (≈ 5nA) were acquired with a Photometrics series 200 CCD camera attached to the MCP/FS detector of the ion microprobe. High-precision data required well-tuned secondary ion optics to minimize image aberrations, appropriate image processing procedures to account for the non-linearity of the MCP/FS detector, and considerable mass consumption (≈ 40%) of the 1µm-sized SiC grains during high mass resolution ion imaging. Under these conditions the Si-isotopic ratios can be determined with a precision of ≈ 45‰ (1σ), sufficient to resolve the Z grains from the mainstream grains. Nineteen Z candidate grains (out of 500 grains that gave good enough ion imaging data) were found (Fig. 1) which were subsequently analyzed for their isotopic compositions of C, N, and Si (13 grains) and of Mg-Al and Si (6 grains) by the conventional SIMS analysis technique.

Nine of the candidate grains were shown to be Z grains, representing about 2% of the SiC grains. This is consistent with the Z grain abundance in Murchison KJE given by [2]. The Z grains of this study have predominantly isotopically heavy C with ^{12}C/^{13}C ratios from 11 to 120, isotopically light N with ^{14}N/^{15}N ratios between 1100 and 19000 (Fig. 2), depletions in ^{29}Si (relative to solar) with δ^{29}Si values from -150 to -15‰, enrichments in ^{30}Si (relative to solar) with δ^{30}Si values between 65 and 510‰ (Fig. 3), and excess ^{26}Mg with inferred initial ^{26}Al/^{27}Al ratios of ≈ 10^{-3}. One Z grain falls close to the Y grain Si correlation line [4] (see Fig. 3) but its low ^{12}C/^{13}C ratio of 11 is clearly lower than the characteristic Y grain ^{12}C/^{13}C ratio of > 140.

The C- and N-isotopic compositions of the Z grains are similar to those of the mainstream grains (Fig. 2), which are believed to have originated from low-mass AGB stars [e.g., 4], but distinct from the X grains, which most likely formed in the ejecta of supernova explosions [6, 7, 8]. The initial ^{26}Al/^{27}Al ratios of the Z grains are also compatible with those of the mainstream grains (10^{-4} to 10^{-3} [4]) and clearly lower than those of the X grains (> 10^{-1} [6, 7, 8]). This implies a close relationship between the Z grains and the mainstream grains and AGB stars as sources of the Z grains are strongly favoured.

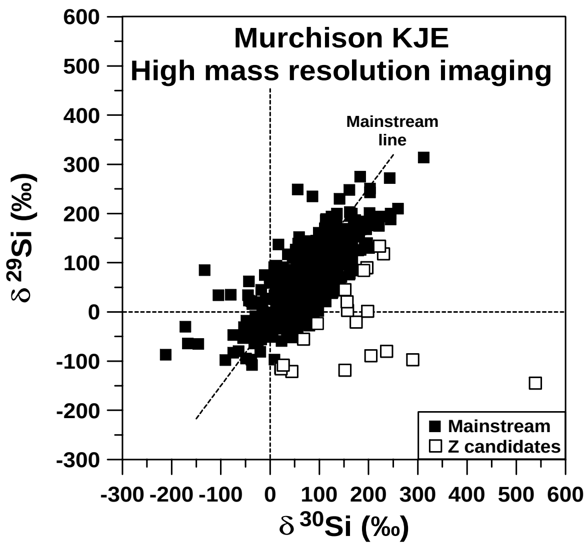

Figure 1. Si-isotopic compositions of Murchison KJE grains obtained from high mass resolution ion imaging.

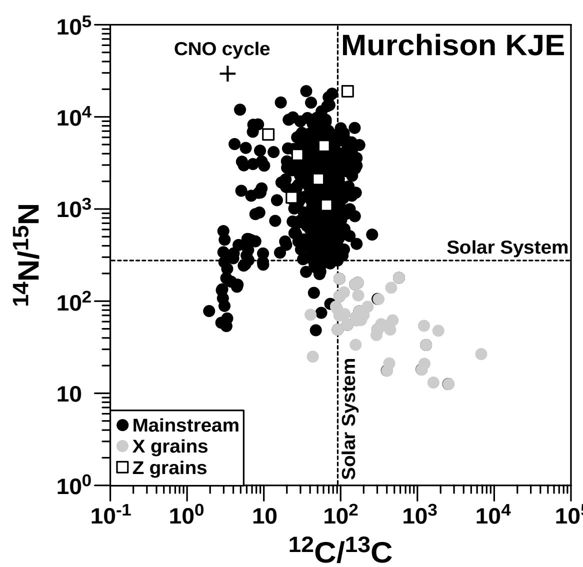

Figure 2. C- and N-isotopic compositions of Murchison KJE grains. Data for mainstream and X grains are from [2, 4, 5].

The mainstream Si correlation line ($\delta^{29}Si = 1.34 \cdot \delta^{30}Si - 16$) probably represents a range of Si starting compositions of a large number of AGB stars at stellar birth established by the galactic chemical evolution [9, 10]. In the models of [9] and [10] the effects of the stellar processing of the Si isotopes are only of minor importance. The large deviations of the Z grains from the mainstream line can be explained by third dredge-ups of large amounts of He shell matter to the stellar envelope. In the He shell the original Si-isotopic composition is altered by the s-process. This enriches ^{29}Si and ^{30}Si and the Si-isotopic composition is expected to evolve away from the mainstream line along a line with slope ≈ 0.5 in a three-isotope-representation [e.g., 11]. From the Z grain data Si starting compositions of $\delta^{29}Si_{ini}$ = -420 to -60‰ and $\delta^{30}Si_{ini}$ = -300 to -30‰ are calculated (Fig. 3). These compositions imply metallicities of the parent stars of [Fe/H] = -0.1 to -0.4 [10]. Calculated Δ^{30}Si (≡ δ^{30}Si - $\delta^{30}Si_{ini}$) values range from 100 to 800‰. Taking the model compositions of [11] a mixing ratio between He shell and envelope matter of between 0.1:1 and 1.4:1 (≡ 10 - 60% He shell matter) is required. It is remarkable that large deviations from the mainstream Si correlation line are found only at the ^{29,30}Si-poor end of the Si array. A possible explanation are smaller ^{29,30}Si enrichments in the He shell of high-metallicity stars which are believed to represent the ^{29,30}Si-rich end of the Si array [10].

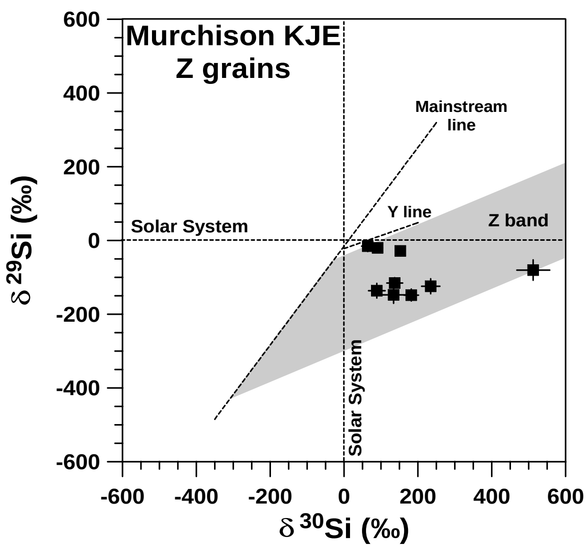

Figure 3. Si-isotopic compositions of Murchison KJE Z grains. The "Z band" assumes Si-isotopic evolution along a line with slope 0.42 [11].

Because He shell dredge-up simultaneously enriches ^{12}C one would expect to find a correlation between the $^{30}Si/^{28}Si$ and $^{12}C/^{13}C$ ratios. This is indeed the case (Fig. 4). The data imply a low $(^{12}C/^{13}C)_{ini}$ ratio prior to the third dredge-up pointing to extensive cool bottom processing during the red giant phase of the parent stars [12]. This limits the mass of the parent stars to 2.3 $M_{\odot}$ because cool bottom processing cannot occor in more massive stars during the red giant phase. The data are roughly consistent with $(^{12}C/^{13}C)_{ini}$ = 3.4 (the equilibrium value of the CNO cycle) and $(C/Si)_{HeShell}/(C/Si)_{envelope}$ = 60 ("AGB evolution line" in Fig. 4).

In summary, the SiC Z grains appear to have formed in the stellar winds of low-metallicity low-mass AGB stars that experienced extensive dredge-up of He shell matter. It remains to be seen, however, whether detailed models of AGB stars will be able to account for He shell dredge-up on the order of several 10%, as required. Many heavy elements (e.g., Ba, Nd, Sm) are strongly enriched in the s-process. They are thus sensitive monitors of the evolution of AGB stars and measurements of the abundances of these elements in single SiC Z grains would help to put further constraints on the Z grain parent stars.

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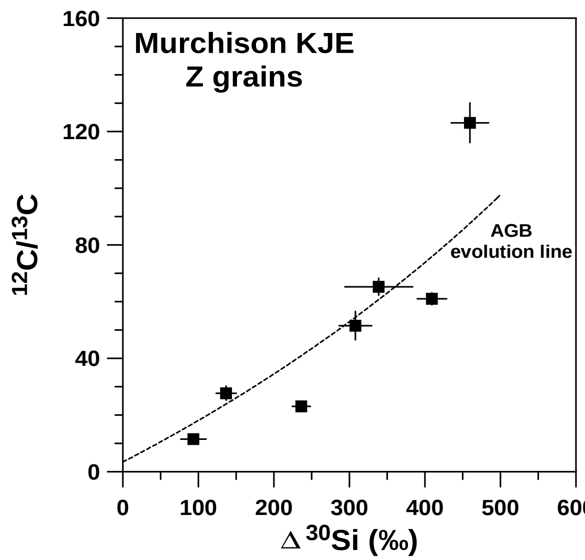

Figure 4. C- and Si-isotopic compositions of Murchison KJE Z grains. Δ^{30}Si is the per mil deviation from the mainstream Si correlation line. The right end of the "AGB evolution line" corresponds to 40% He shell matter.

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